N73-12144

A 15.3 GHz SATELLITE-TO-GROUND DIVERSITY EXPERIMENT UTILIZING THE ATS-5 SATELLITE

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TECHNICAL REPORT 2374-11

October 1972

Grant Number NGR 36-008-080

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National Aeronautics and Space Administration
Office of Grants and Research Contracts
Washington, D.C. 20546

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REPORT 2374-11

REPORT
by
THE OHIO STATE UNIVERSITY ELECTROSCIENCE LABORATORY
Columbus, Ohio 43212

Sponsor	National Aeronautics and Space Administration Office of Grants and Research Contracts Washington, D.C. 20546
Grant Number	NGR 36-008-080
Investigation of	Millimeter-Wavelengths Propagation Studies
Subject of Report	A 15.3 GHz SATELLITE-TO-GROUND DIVERSITY EXPERIMENT UTILIZING THE ATS-5 SATELLITE
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Submitted by	D. B. Hodge ElectroScience Laboratory Department of Electrical Engineering The Ohio State University
Date	October 1972

ABSTRACT

During 1970 and 1971 the characteristics of a diversity satellite-to-ground communication link were measured using the ATS-5 15.3 GHz downlink. These data were gathered at two ground receiving terminals spaced 4 km apart during 1970 and 8 km apart during 1971 in the vicinity of Columbus, Ohio. These data have been subsequently analyzed to determine the improvement in link performance resulting from the use of space diversity. The results of this analysis have shown that substantial improvements in link performance may be gained through the use of space diversity on satellite-to-ground paths. For example, the durations of fades having depths exceeding 10 dB were reduced by more than two orders of magnitude for both the 4 and 8 km site separation distances.

ACKNOWLEDGMENTS

The author wishes to acknowledge the substantial efforts of P. Bohley, R.C. Taylor, L. Zintsmaster, and K.G. Grimm in the design and execution of this measurement program. The author is also grateful for the generous cooperation of the U.S. National Weather Service in providing weather information; the Ohio State University Department of Athletics, the Ohio State Farm Science Review, and the Ohio State University Department of Animal Science in providing sites for the transportable terminal; and the City of Upper Arlington, Ohio, in providing assistance during the relocation of the transportable terminal.

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I. INTRODUCTION

It has been well established that deep fades will be encountered for significant periods of time on millimeter wavelength earth-satellite links[1]. These fades are a result of intense rain rates generally associated with thunderstorm cells located along the propagation path. The durations of such fades have been observed to exceed several tens of minutes in some instances and tend to be the limiting factor in the overall reliability of millimeter wavelength communication systems. Since the thunderstorm cells which give rise to the more severe fades are limited in both horizontal and vertical extent it has been proposed that two or more ground terminals operated in a space diversity mode might provide an effective means of reducing this limitation to system reliability[2]. The two ground terminals would be spatially separated so that the percentage of time that both terminals simultaneously experience significant fading is reduced well below that of a single terminal. The received signals from both terminals could then be compared and the larger of the two selected by simple switching.

Since sufficient rain rate distribution data were not available for the prediction of the performance of such a diversity system, a diversity experiment was performed by the Ohio State University ElectroScience Laboratory utilizing the 15.3 GHz downlink available on the ATS-5 synchronous satellite. Two ground receiving terminals, located in the vicinity of Columbus, Ohio, were operated at a separation distance of 4 km during 1970 and 8 km during 1971. The received signal level was recorded at each terminal and compared during subsequent processing in order to simulate the performance of a diversity system operating in real time. Thus, in effect, the fade distributions associated with each individual terminal as well as the fade distribution of the two terminals in a diversity mode were measured. In addition to the measurement of attenuation, the radiometric temperature along the propagation path was also measured at each terminal. These radiometric temperature data were then correlated with the attenuation data in order to assess the utility of radiometric temperature measurements in the prediction of attenuation statistics.

II. INSTRUMENTATION

The 15.3 GHz CW transmitter on board the ATS-5 synchronous satellite provided the coherent signal source for this experiment. Unfortunately, the satellite suffered a malfunction such that the satellite could not be despun after injection into its orbital slot. This spinning motion caused the pattern of the transmitting antenna to sweep across the earth approximately every 0.78 seconds; therefore, the signal received at the ground terminals consisted of pulses having a repetition rate of about 1.27 Hz and a 3 dB width of 45 ms.

In addition to this signal variation, a slight tilt of the satellite spin axis with respect to the earth's axis also produced a sinusoidal diurnal variation having a peak-to-peak value of 3 to 4 dB. Both of these conditions remained stable and predictable throughout the duration of the experiment. Both the main and the back-up transmitter on board the spacecraft experienced some output power degradation during the experiment; as a consequence, most of the measurements were performed under conditions resulting in a system margin on the order of 12 to 14 dB.

Two ground terminals, one fixed and the other fully transportable, were instrumented for this experiment. The fixed terminal was located at the Ohio State University Satellite Communications Facility and utilized a 30 ft. parabolic antenna during the 1970 data period. This antenna was replaced by a 15 ft. parabolic antenna having improved surface tolerance and wind loading characteristics during the 1971 data period; the improvement in surface tolerance compensated for the reduction in aperture area associated with this change. The transportable terminal utilized a 15 ft. parabolic antenna mounted on a trailer and an equipment van which was completely self-contained with the exception of a primary power source. Top and side views of the relative locations of the transportable terminal during the two measurement periods are shown in Figs. 1 and 2. The azimuth and elevation angles were nominally 210° and 38°, respectively. Both antennas were Cassegrainian fed and were illuminated by square, corrugated horns designed to produce identical E- and H-plane patterns with reduced side-lobes. A polarization splitter at the throat of the horn permitted the two orthogonal polarization components to be separated and fed, respectively, to the receiver and the radiometer. Both antenna feed-horns were aligned so that the receiver polarization coincided with that of the satellite signal. Thus, the radiometer viewed the same volume as that seen by the receiver, although the polarizations were orthogonal.

The receivers at both terminals were Martin-Marietta phase-locked-loop (PLL) receivers supplied by NASA. These receivers incorporated single stage tunnel diode RF amplifiers and included complete calibration and test circuitry. These receivers were able to maintain phase lock with the pulsed satellite signal down to approximately -135 dBm. Both radiometers were of the Dicke type having 1 sec. integration times. The detected outputs of the PLL receiver and radiometer, along with meteorological parameters and various station keeping data, were recorded on a 14-track analog tape recorder at each terminal. The outputs of the PLL receiver and radiometer were also recorded on strip charts for convenient reference. A BCD time code, as well as a 1 pps. reference signal, was also recorded on this analog tape. The resulting analog data tapes were subsequently digitized at a real time rate of 250 samples per second. The pulse amplitudes were then digitally detected and recorded on

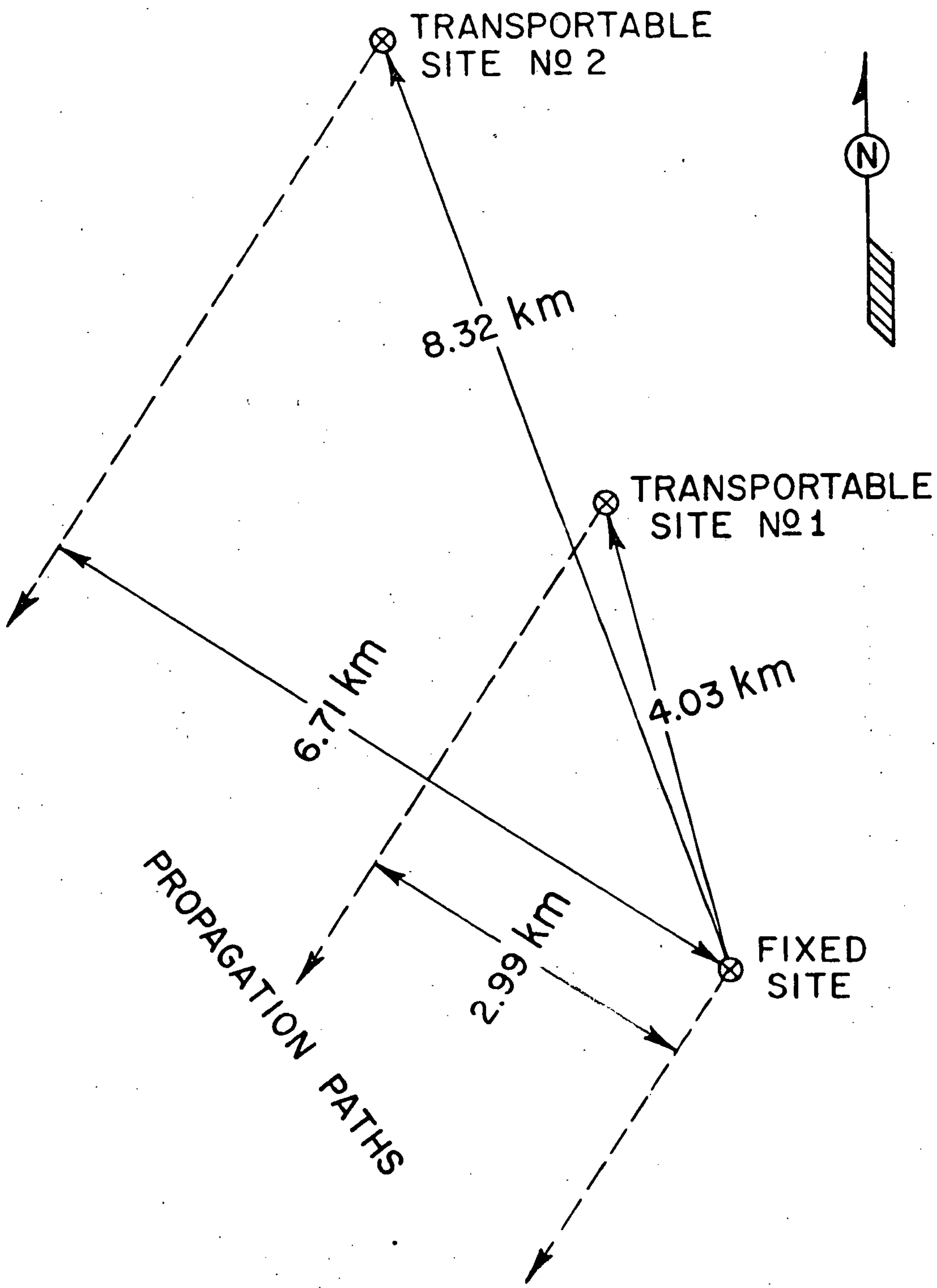
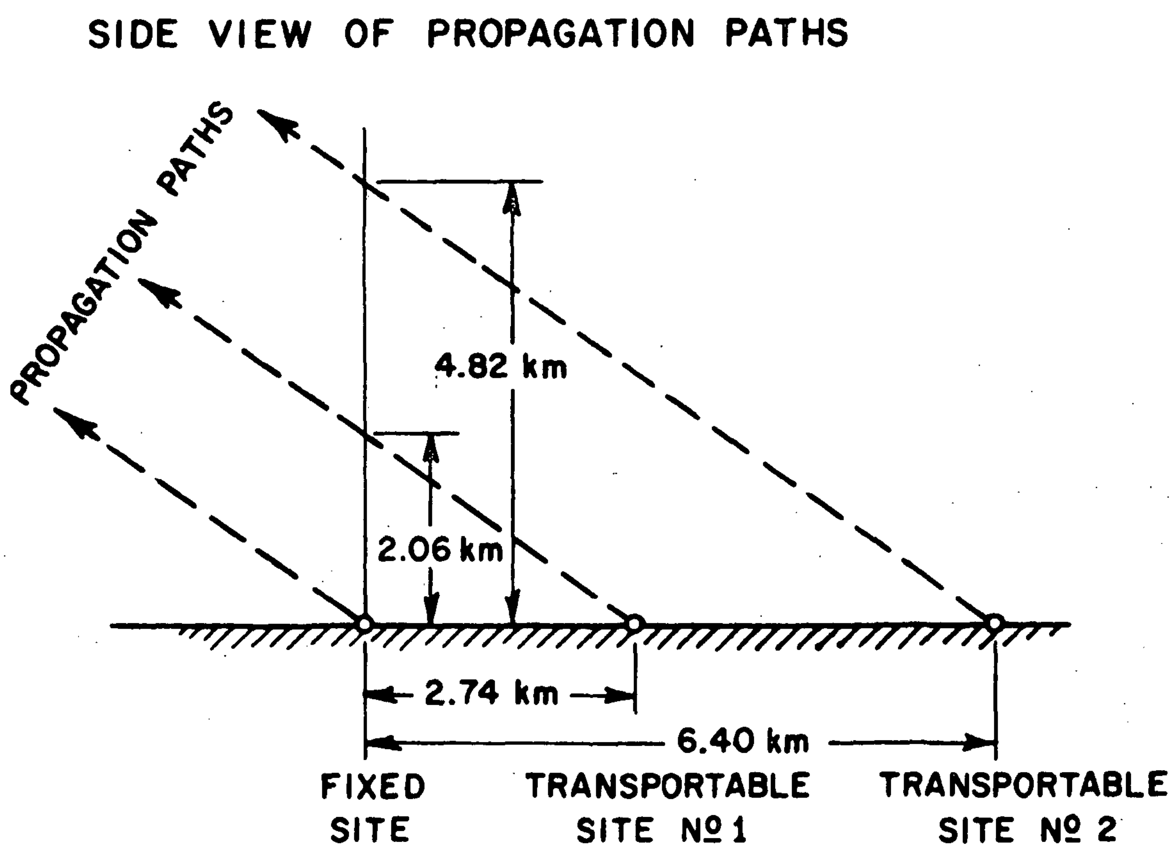


Fig. 1. Top view of site locations.



SITE	PATH SEPARATION		
	HORIZONTAL	VERTICAL	SPATIAL
№ 1	2.99 km	2.06 km	3.41 km
№ 2	6.71 km	4.82 km	7.73 km

Fig. 2. Side view of site locations.

digital magnetic tape for further analysis. An overall system analysis indicated that the estimated error of the attenuation measurements was within 1.4 dB and that of the radiometric sky temperature was 6°K.

III. DATA

Data were recorded during periods of thunderstorm activity as predicted by weather radar observations, aviation weather bulletins, or consultation with local National Weather Service forecasters. Following each data run, typically one to three hours in duration, the PLL receiver and analog tape recorder were calibrated completely. A calibrated noise source was used to check and adjust for radiometer drift at approximately half-hour intervals during data run periods.

Analog data tapes from all data runs were provided to NASA/GSFC for analysis as part of the ATS-5 Millimeter Wave Experiment. Those data runs in which fading in excess of 2 dB was observed at either terminal were selected for digitization and diversity analysis; these data serve as the basis for the results discussed in this paper. The duration of diversity data analyzed was 55 hours, 8 minutes at the 4 km separation distance and 31 hours, 4 minutes at the 8 km separation distance.

In all measured events, the onset and conclusion of fading were well defined; these periods were preceded and followed by periods of relatively stable signal levels, i.e., signal variations significantly less than one decibel. Data periods to be analyzed were chosen to commence during the stable period just prior to the earliest evidence of fading at either terminal and to conclude when the signal level at both terminals had returned to the stable level. Since these periods were only of the order of an hour or two in duration, the variation in signal level due to the diurnal variation was small and could be neglected in the succeeding analysis. All signal levels were measured relative to the stable signal level which existed before the onset of fading; thus the resulting statistics refer to "excess" attenuation produced by precipitation along the propagation path and do not include attenuation due to atmospheric gases and cloud cover present prior to the periods of significant fading.

IV. RADIOMETRIC SKY TEMPERATURE

The received signal level was compared with the radiometric sky temperature, as shown in the sample scatter plot in Fig. 3, in order to determine the utility of radiometric measurements in estimating path attenuations. Each point in this plot represents the average of 10 successive pulses. The solid curves represent the relationship

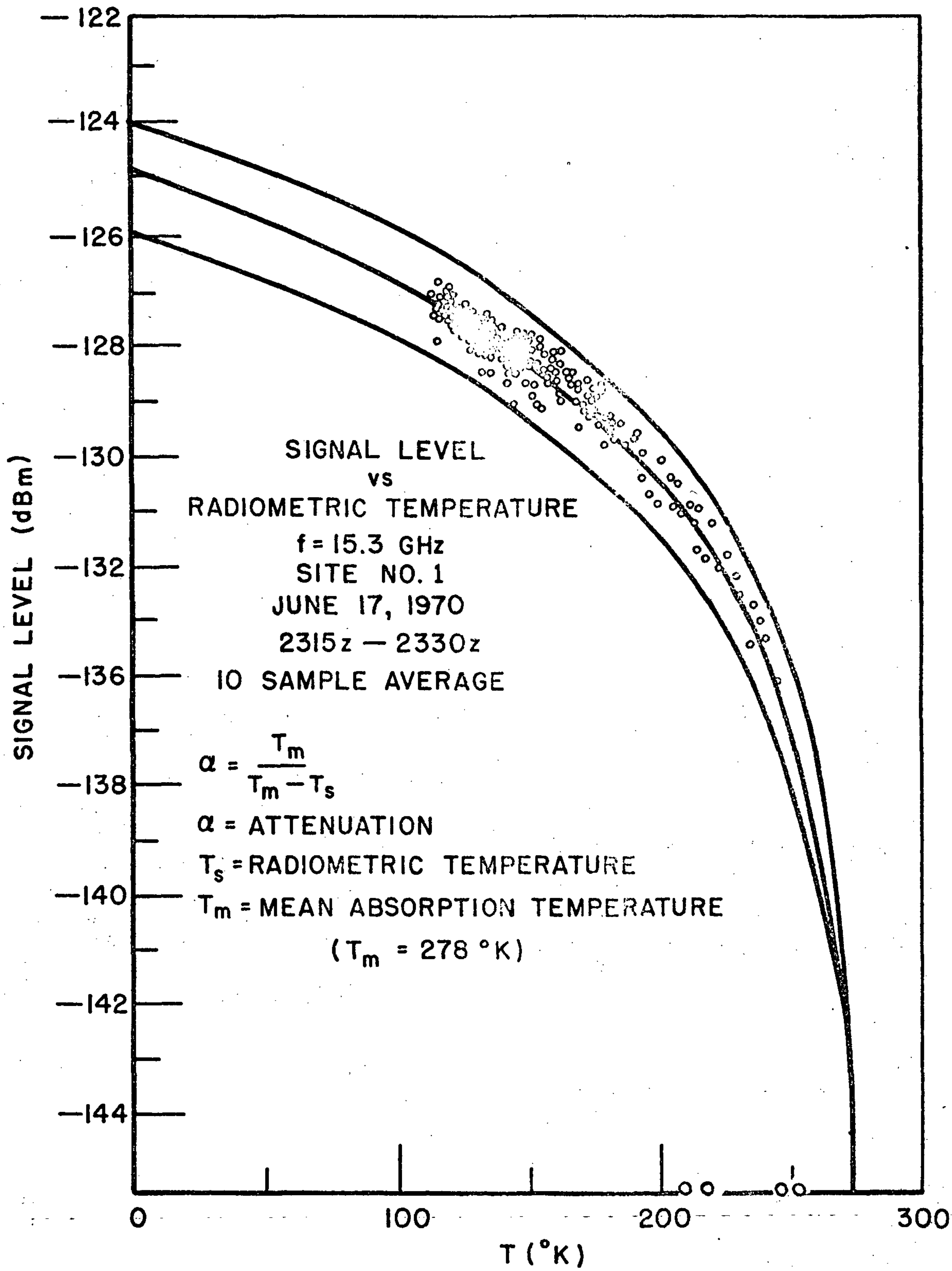


Fig. 3. Received signal level vs radiometric temperature during 2315Z-2330Z on June 17, 1970.

between attenuation and radiometric temperature in a homogeneous, lossy medium at temperature T_m:

$$\alpha = \frac{T_m}{T_m - T_s}, \tag{1}$$

where α is the total path attenuation and T_s is the radiometric sky temperature[3]. The family of three solid curves represents the uncertainty associated with a ±1 dB variation in the absolute received signal level.

Cross correlation coefficients between the received signal level and the radiometric sky temperature were calculated for each of the 1970 data periods; these ranged from 0.67 to 0.96. The cumulative cross correlation coefficient for the 1970 data was 0.81 for the fixed terminal and 0.92 for the transportable terminal[4]. This relatively high degree of correlation is, nevertheless, probably pessimistic since the antenna pointing was manually controlled. Any small pointing error would reduce the received signal level while not appreciably affecting the radiometer temperature. The lower cumulative correlation value for the fixed terminal was a result of this effect.

Thus, the data were found to agree well with a simple, homogeneous model of a lossy atmosphere. The useful dynamic range of this model is limited to about 12 dB when estimating path attenuation from radiometric data due to the relative independence of highly attenuated signal levels on radiometric temperature. This agreement, of course, presupposes that the beamwidth of the radiometer is narrow enough to exclude even fine scale inhomogeneities in the atmosphere which do not influence the line-of-sight propagation path. In addition to attenuation estimates, the radiometers were also found to provide an excellent operational aid in conjunction with the operation of the satellite link. It was found that a decrease observed in the received signal level without a corresponding increase in radiometric temperature very reliably indicated an error in antenna pointing or a malfunction in the receiver system.

V. CROSS CORRELATION BETWEEN RECEIVED SIGNALS

Cross correlation coefficients between the attenuations observed at the two separated terminals were also calculated. The cumulative cross correlation coefficients were 0.45 for the data taken with a 4 km separation and 0.27 for the 8 km separation. The delay times associated with the occurrence of maximum cross correlation were 4.1 min. and 10.2 min. for the 4 and 8 km data, respectively. These values are somewhat biased due to the fact that they were computed from selected periods of severe fading; nevertheless, they do indicate

in a qualitative manner the time delay between cell passage across the two propagation paths and the extent of the difference in cell structure seen along the two separated propagation paths. The positive value of time delay was associated with the occurrence of fading first at the transportable terminal which agrees with the general tendency of thunderstorm cells to travel in an Easterly direction.

VI. FADE DISTRIBUTIONS AND DIVERSITY GAIN

The fade distributions observed at the individual terminals as well as the fade distribution resulting from the space diversity mode of operation were also examined. These results for the 4 and 8 km separation distances are shown in Figs. 4 and 5, respectively. As expected, the individual terminal fade distributions are quite similar for the 4 km separation and show less similarity for the 8 km separation. The diversity fade distributions, labeled "BOTH" in the figures, were obtained by digitally comparing the individual terminal received signal records and selecting the larger signal on a pulse-by-pulse basis. This method of analysis corresponds to a simple switched diversity system operating in real time. The most rapid fade rate observed during deep fading in the course of these measurements was approximately 1/8 dB per second. Thus one may conclude that even a very slow switching scheme will be quite adequate for diversity operation in the presence of precipitation fading.

The description of system improvement in terms of diversity gain provides a means of separating, to some extent, the effect of terminal separation from variations in the individual terminal fade distributions. Diversity gain may be defined as the difference between the signal level resulting from the diversity mode of operation and the median of the individual terminal received signal levels, both evaluated at a given percentage of occurrence. The diversity gain then corresponds to the improvement derived from diversity operation as compared to single terminal operation over a long period of time. Diversity gain data for both the 4 and 8 km separation distances as a function of single terminal fade depth are shown in Fig. 6. Note that the abscissa itself corresponds to diversity operation with zero separation, and the straight line with unity slope through the origin corresponds to the ideal case in which diversity operation eliminates all fading. Obviously, then, the 4 and 8 km diversity data must lie between these two limiting cases. Note, also, that the experimental data fall very nearly on straight lines having approximately unity slopes for fade depths exceeding 10 dB for the 4 km separation and 4 dB for the 8 km separation. This characteristic indicates that the diversity system is operating very much like an ideal system for fade depths below these levels and is, indeed, quite effective in improving system performance during periods

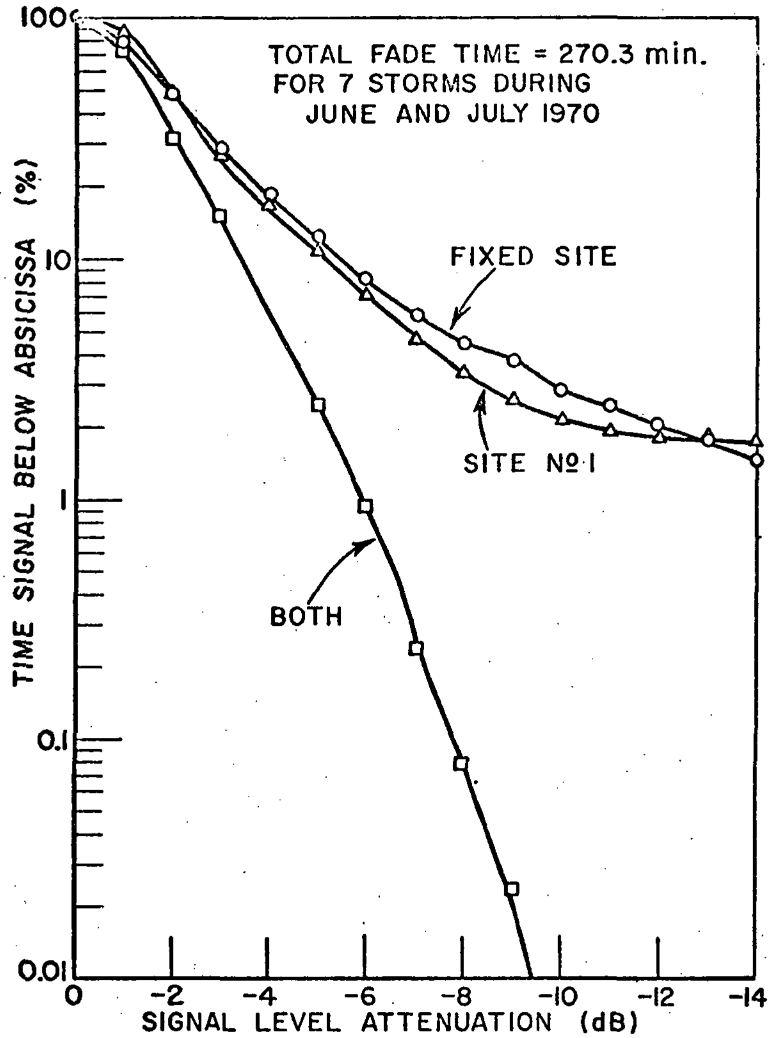


Fig. 4. Fade distributions for 4 km data.

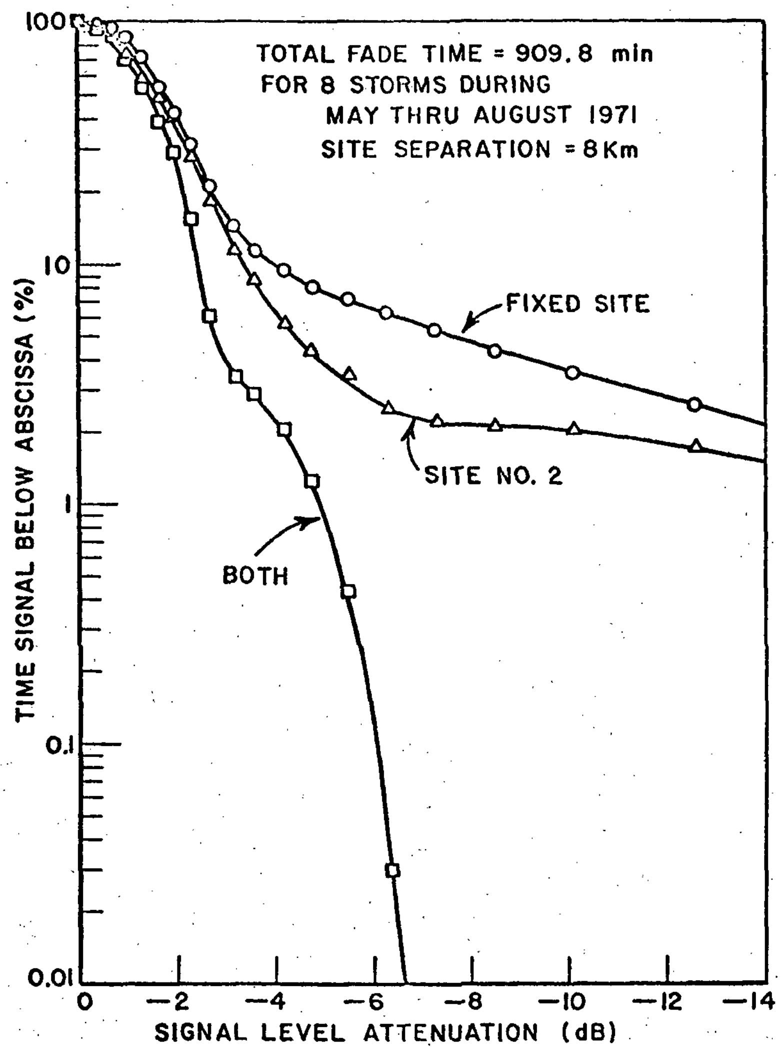


Fig. 5. Fade distributions for 8 km data.

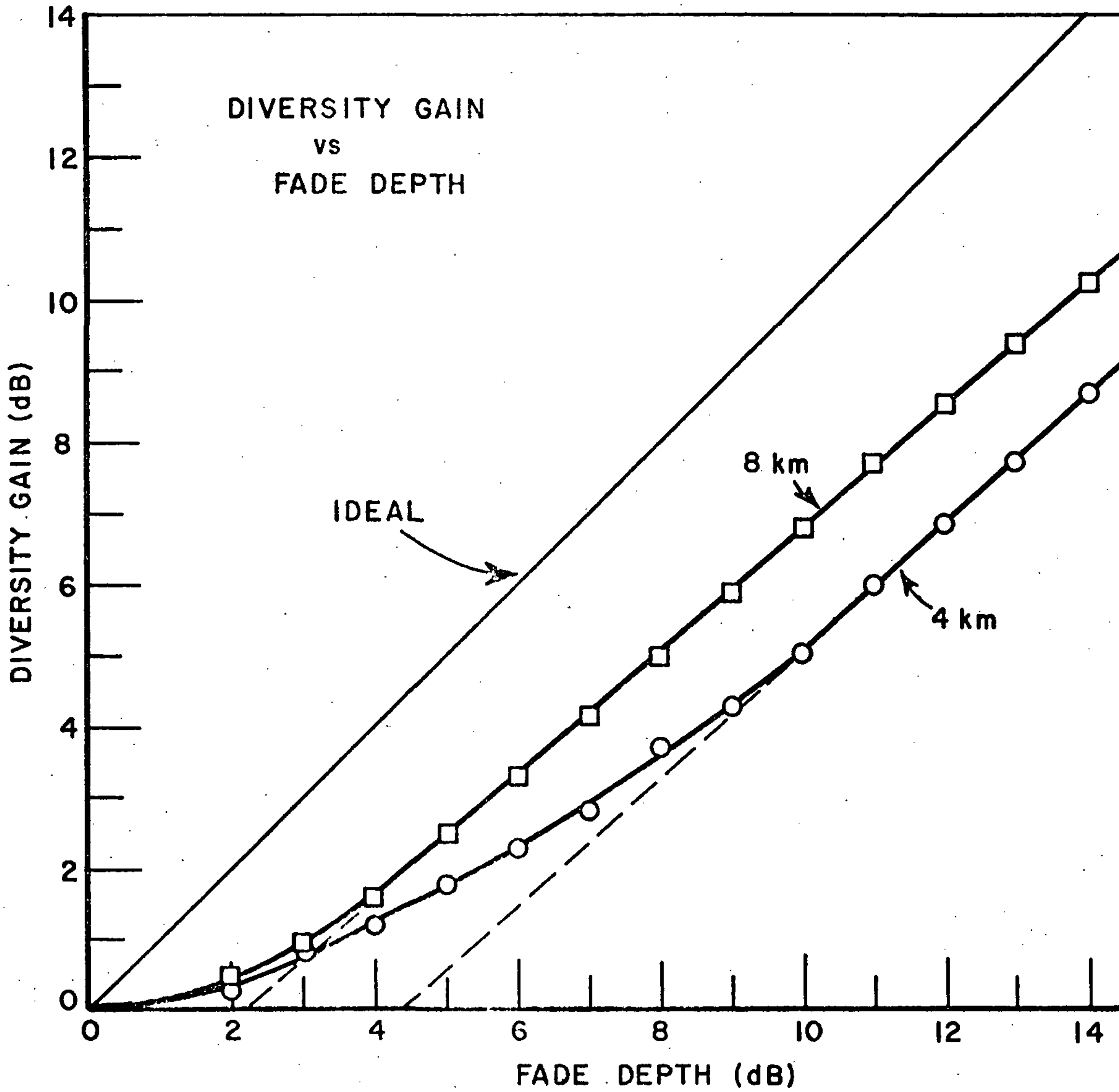


Fig. 6. Diversity gain versus single terminal fade depth.

of deep fading. Further examination of the diversity gain data indicates that the use of larger terminal separation distances will provide proportionally less improvement in system performance. This reduced degree of improvement will also be purchased at the increased cost of the data link between the two ground terminals required for real time diversity operation.

These diversity gain data are also compared in Fig. 7 with radiometric diversity data measured by Wilson at Crawford Hill, N.J. The Bell Telephone laboratories data shown in this figure were extracted from Fig. 1 in Ref. [5]. Wilson's measurements were made with the baseline of the radiometers nearly perpendicular to the propagation path. The similarities in these data tend to confirm the fact that significant improvements in system reliability will result from the use of diversity terminals separated by relatively small distances, on the order of 4 to 8 km. Any benefits to be derived from larger separation distances may be overshadowed by the increasing probability of two different cells producing attenuation on the separated propagation paths.

Additional factors which must be considered when designing diversity systems and predicting their performance are enumerated below. The size, shape, and orientation of the intense thunderstorm cells which produce severe attenuation must be known in order to weigh the relative merits of placing the terminals along a base line perpendicular to the propagation path in contrast with placement along the propagation path. In the case of earth-satellite links, placement along the propagation path permits one to take advantage of the finite vertical extent of the attenuating region within the thunderstorm cell; such an alternative does not exist for ground based links. Furthermore, these cell characteristics tend to vary from one climatic region to another, necessitating the need for this information as a function of geographical location. Finally, it may be necessary to reconsider the use of annual fade distributions as the prime criterion in the assessment of millimeter wavelength system reliability due to the seasonal and diurnal variations of precipitation attenuation. For example, in the midwest it is much more likely that severe attenuation will occur during the late afternoon or early evening hours from spring through midsummer. As a consequence the system reliability during these periods may be reduced substantially below that indicated by fade distributions averaged throughout the entire year.

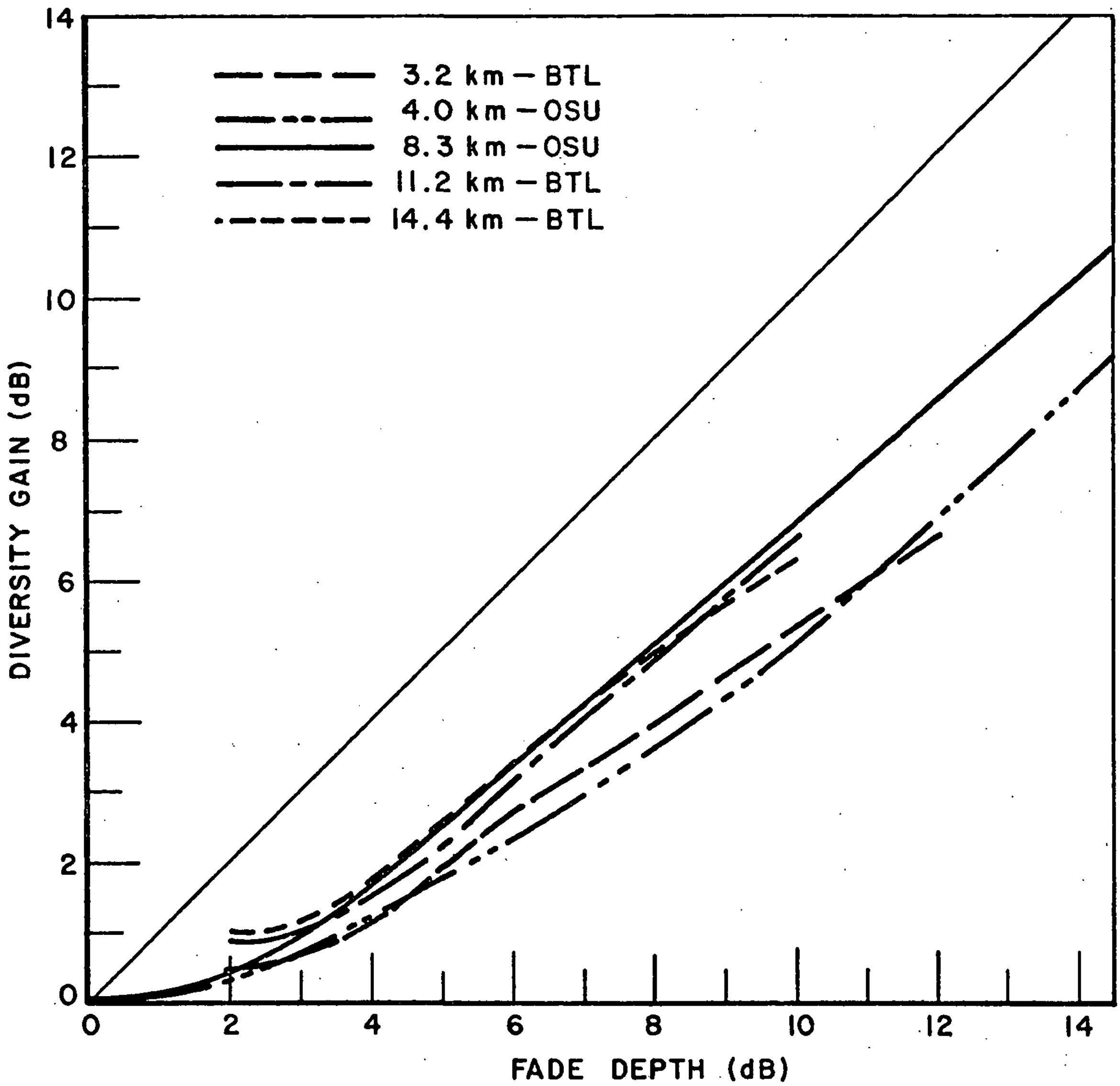


Fig. 7. Comparison of BTL and OSU diversity data.

VII. SUMMARY

Data characterizing the operation of a millimeter wavelength, earth-satellite, diversity communication link in the midwest have been presented. These data indicate that substantial improvements result from the use of receiving terminals separated by distances of 4 or 8 km. Statistically, fades depths of 10 dB are effectively reduced to 5.0 and 3.2 dB, respectively, in the diversity mode of operation. Simultaneous measurements of attenuation and sky temperature using a narrow beam radiometer oriented along the propagation path have also confirmed the usefulness of radiometric temperature measurements in the prediction of attenuation levels up to about 12 dB.

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